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THE EMISSIVITY OF METALS AND OXIDES

II. MEASUREMENTS WITH THE MICROPYROMETER

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As indicated in a communication describing the micropyrometer,¹ this instrument may be used conveniently for the approximate determination of the monochromatic emissivities of metals, oxides, and other substances in microscopic quantities at high temperatures. This method has the further advantages of simplicity and rapidity of operation and also permits the taking of observations on rare elements, alloys, and compounds which are available only in minute quantities. It is possible, for example, under favorable conditions to measure with an accuracy of about 1 per cent the emissivity of a substance having a mass of 0.01 mg, an area of 0.25 mm², and thickness of 0.005 mm. The method lends itself readily to the determination of a temperature coefficient of emissivity and to the detection of a variation of emissivity with change of state, as at the melting point. The temperature range of the micropyrometer for these purposes is from about 700 to 3000° C.

THE METHOD

In the form here used this is a secondary method, requiring a substance of known emissivity as a comparison standard. For this purpose platinum is taken, and in what follows it is assumed that for solid platinum, at all temperatures, $e=0.33$ for $\lambda=0.650\mu$ and $e=0.38$ for $\lambda=0.547\mu$. The method is most precise for substances having an emissivity nearly equal to that of the comparison substance.

¹ G. K. Burgess, A Micropyrometer, Jour. Wash. Acad., 3, p. 7, 1912; Bulletin Bureau of Standards, 9, p. 475, 1912.

For the determination of its emissivity, a speck of the substance, say 0.01 mg, is placed on a platinum strip, or one of iridium or tungsten for substances melting above 1750° C, contained in a suitable atmosphere, as air, hydrogen, or in a vacuum. The strip is heated electrically until the speck melts, when, if observations on the emissivity of the solid are to be taken, the temperature of the strip is immediately lowered below the freezing point to prevent alloying. The solid substance should now have a plane, clean surface, and observations of its emissivity in terms of that of platinum may then be taken. For this purpose the micropyrometer, provided with a suitable monochromatic glass in the eyepiece, and for very high temperatures with a calibrated absorption glass before the objective of the microscope, is brought alternately to the same brightness as the platinum strip and the surface the emissivity of which is sought; the apparent temperatures of the surfaces are then measured in succession. With liquid metals observations have to be taken rapidly and before the effects of alloying have reached the surface.

The micropyrometer is first calibrated for use with a platinum or other strip by the method of known melting points (*loc. cit.*). For convenience in computation the calibration may be expressed graphically in terms of the equivalent or "black-body" temperatures p of platinum for any given wave length.² The pyrometer sighted on the platinum strip then gives p directly from which t the same true temperature of the platinum and substance is obtained graphically; sighting on the substance gives s , its equivalent temperature directly.

The emissivity, e_λ , of the substance is then calculated from Wien's equation:

$$\log_{10} e = \frac{c \log E}{\lambda} \left(\frac{1}{T} - \frac{1}{S} \right)$$

in which $c = 14,450$, E the Napierian base, λ the wave length, T and S the absolute true and equivalent temperatures of the substance.

² See G. K. Burgess, Note on Graphic Solutions of Wien's Spectral Equation, *Jour. Wash. Acad.*, 1, p. 205, 1911.

Both tungsten and carbon lamps with fine filaments were used in the micropyrometer. Either type of lamp gave satisfactory and reliable results, the greater current sensibility of the carbon lamps about balancing the sharper photometric match of the tungsten when sighting on a metallic surface.

THE OBSERVATIONS

Measurements have been taken, mainly with red and green light of wave lengths 0.650μ and 0.547μ , respectively, of the emissivity of a number of metals and oxides over a considerable temperature range both in the solid and liquid states. The principal results for the metals are shown in Table 1, together with those obtained by other observers.

It will be seen that the emissivities determined by the micropyrometric method agree for the most part with those obtained by others when working with substances upon which good surfaces may be maintained. For example, comparison of the results here obtained with those of Stubbs and Prideaux on solid and liquid gold, silver, and copper indicates differences of 0° to 5° C in the determination of the equivalent temperatures. The values found with the micropyrometer are for several other substances practically identical with those obtained by other methods; thus, compare in Table 1 the values for Pd, Ir, Rh, Ni, and Fe.

TABLE I
Measurements of Emissivity of Elements

| Substance | Micropyrometer observations | | | | Other observers | | | |
|------------|-----------------------------|------------------------------|--------------|------------------------------|----------------------|----------|-------------------------------|---|
| | Solid | | Liquid | | At room temperatures | | At high temperatures | |
| Atmosphere | Temp. °C. | Emissivity $\lambda 0.65$ | Temp. °C. | Emissivity $\lambda 0.65$ | e $\lambda 0.65$ | Observer | e $\lambda 0.65$ | Observer |
| Copper | H | .930 | 0.096 | 1100 | 0.150 | 0.36 | Drude ³ | Solid, Stubbs ⁴ |
| | | 1025 | .105 | | | .11 | Hagen and Rubens ⁶ | Liquid, Stubbs ⁴ |
| Silver | H | 1080 | .117 | 0.38 | | .229 | Tate ⁶ | Burgess ⁷ |
| | | | | 980 | .072 | <.35 | Tool ⁸ | Bidwell ⁹ |
| Gold | H | 940 | .044 | <.35 | | .047 | Drude ³ | Holborn and Henning ¹⁰ |
| | | | | | | .065 | Hagen and Rubens ⁶ | Liquid, Stubbs ⁴ |
| Palladium | H | 1000 | .145 | <.38 | 1065 | .219 | <.38 | Henning ¹¹ |
| | | | | | | .048 | Tate ⁶ | Bidwell ⁹ |
| Platinum | H | 1530 | .33 | .38 | 1555 | .37 | | Drude ³ |
| | | | | | | | .111 | Hagen and Rubens ⁶ |
| | | | | | | .154 | Tate ⁶ | Solid, Stubbs and Prieur ¹² |
| | | | | | | .095 | Tool ⁸ | Liquid, Stubbs and Prieur ¹² |
| | | | | | | | Wartenberg ¹³ | Waldner and Burgess ¹⁴ |
| | | | | | | | .34 | Waldner and Burgess ¹⁴ |
| | | | | | | | .335 | 975° |
| | | | | | | | .295 | Waldner and Burgess ¹⁴ |
| | | | | | | | .135° | Waldner and Burgess ¹⁴ |
| | | | | | | | .335 | 975° |

| | | | |
|---------|---|------------------------------------|------------------------------------|
| .337 | Hagen and Rubens ⁶ | .285 | Waldner and Burgess, ¹⁴ |
| .32 | Henning ¹¹ | .30 | Féry and Cheneveau, ¹⁵ |
| | Wartenberg, ¹³ 0.257 ($\lambda=0.579$) | .36 | Féry and Cheneveau, ¹⁶ |
| | | .35 | Féry and Cheneveau, ¹⁵ |
| | | .32 | Henning ¹¹ |
| | | .319 | Holborn and Henning ¹⁰ |
| | | .34 | McCauley, ¹⁹ 820° |
| | | .30 | McCauley, ¹⁶ 1120° |
| | | .27 | McCauley, ¹⁶ 1680° |
| | | .34 | Pitani ¹⁷ |
| | | .295 | Spence ¹⁸ |
| | | .28 | Wartenberg ¹³ |
| | | .33 | Laue and Martens ¹⁹ |
| | | .31 | Henning ¹¹ |
| | | .25 | Wartenberg ¹³ |
| | | .29 | Henning ¹¹ |
| | | .20 | Wartenberg ¹³ |
| | | .36 | Henning ¹¹ |
| | | .355 | Bidwell ⁹ |
| | | .335 | Tool ⁸ |
| Iridium | H 1750 .298 | .24 Coblenz ²⁰ | Wartenberg ¹³ |
| | | .32 Henning ¹¹ | |
| Rhodium | H <M. P. .29 .29 >M. P. .30 | .259 Wartenberg ¹³ | |
| Nickel | H 1200 .36 .44 1460 .37 .46 | .22 Coblenz ²⁰ | |
| | H to 1450 | .28 Henning ¹¹ | |
| | | .203 Wartenberg ¹³ | |
| | | .337 Bernoulli ²¹ | |
| | | .363 Drude ³ | |
| | | .341 Hagen and Rubens ⁶ | |
| | | .36 Henning ¹¹ | |

³ Drude, Wied. Annalen, **39**, p. 537, 1890.

⁴ Stubbs, Proc. Roy. Society, Series A, vol. 88, pp. 195-205, 1913.

⁵ Hagen and Rubens, Annalen der Physik, **8**, p. 16, 1902.

⁶ Tate, Physical Review (*1*), **34**, p. 321, 1912.

⁷ Burgess, Bureau of Standards Scientific Paper No. 121.

⁸ Tool, Physical Review (*1*), **31**, pp. 1-35, 1910.

⁹ Bidwell, Physical Review (*1*), **8**, pp. 439-449, 1914.

¹⁰ Holborn and Henning, Sitzungsber. d. Berl. Akad., **12**, p. 311, 1905.

¹¹ Henning, Zs. für Instrumentenkunde, **30**, pp. 67-75, 1910.

¹² Stubbs and Prudeaux, Proc. Roy. Society, Series A, vol. 87, pp. 457-465, 1912.

¹³ Wartenberg, Verh. der Deutschen Phys. Gesellschaft, **12**, pp. 105-127, 1910.

¹⁴ Waldner and Burgess, Bureau of Standards Scientific Paper No. 55.

¹⁵ Féry and Cheneveau, Comptes Rendus, **146**, pp. 407-404, 1908.

¹⁶ McCauley, Astrophysical Journal, **37**, pp. 164-183, 1913.

¹⁷ Pitani, Verh. der Deutschen Phys. Gesellschaft, **18**, p. 19, 1911.

¹⁸ Spence, Astrophysical Journal, **37**, pp. 194-297, 1913.

¹⁹ Laue and Martens, Physikalische Zeitschrift, **8**, p. 833, 1907.

²⁰ Coblenz, Bureau of Standards Scientific Paper No. 152.

²¹ Bernoulli, Annalen der Physik (*4*), **29**, p. 596, 1909.

TABLE I—Continued
Measurements of Emissivity of Elements—Continued

| Substance | Atmosphere | Micropyrometer observations | | | | | | Other observers $\lambda = 0.65$ | At high temperatures $\lambda = 0.65$ | | |
|-----------|------------|-----------------------------|--------------------------------|--------------|--------------------------------|-------------------------|-------------------------------|-------------------------------------|--|--|--|
| | | Solid | | Liquid | | At room temperatures | | | | | |
| | | Temp. °C. | Emissivity $\lambda = 0.65$ | Temp. °C. | Emissivity $\lambda = 0.65$ | e $\lambda = 0.65$ | Observer | | | | |
| Cobalt | H | 1280 | .36 | 1500 | .37 | .319 | Tol ⁸ | | | | |
| | | to | | | | | | Bidwell, ²² 1030° | | | |
| | | 1420 | | | | | | Bidwell, ²² 1330° | | | |
| Iron | H | 1050 | .379 | 1535 | .365 | .415 | Coblenz ²⁰ | .53 | | | |
| | | 1350 | .372 | | | .415 | Drude ⁹ | .40 | | | |
| | | 1450 | .363 | | | .441 | Hagen and Rubens ⁶ | .38 | | | |
| | | 1530 | .360 | | | .422 | Tale ⁶ | .36 | | | |
| | | | | | | .427 | Tool ⁸ | | Liquid | | |
| | | | | | | | | Bidwell, ²² 1530° | iron | | |
| | | | | | | | | Bidwell, ²² 1530° | | | |
| Manganese | H | 1200 | .59 | 1450 | .59 | .59 | | | | | |
| Titanium | H | 1550 | .63 | .75 | 1800 | .65 | | | | | |
| Zirconium | H | <M. P. | .32 | >M. P. | .30 | .75 | | | | | |
| Thorium | H | <M. P. | .36 | >M. P. | .40 | | | | | | |
| Yttrium | H | <M. P. | .35 | >M. P. | .35 | | | | | | |
| Erbium | H | <M. P. | .55 | >M. P. | .38 | .30 | | | | | |
| Beryllium | H | <M. P. | .61 | >M. P. | .61 | .81 | | | | | |
| Columbium | H | <M. P. | .49 | >M. P. | .40 | | | | | | |
| Vanadium | H | 1570 | .35 | .29 | 1800 | .32 | | | | | |
| Chromium | H | 1460 | .39 | .53 | 1550 | .39 | | | | | |
| | | | | | | | | .44 | | | |
| | | | | | | | | | | | |

Wartenberg,¹² 0.365 ($\lambda = 0.579$)
Wartenberg,¹² 0.587 ($\lambda = 0.579$)
Coblenz²⁰
Wartenberg,¹² 0.425 ($\lambda = 0.579$)
Coblenz²⁰
Wartenberg,¹² 0.303 ($\lambda = 0.570$)

| | | | | | | | | | | |
|------------|---|--------|-----|------|--------|-----|------|--|------|---------------------------------------|
| Molybdenum | H | 2000 | .43 | 2500 | .40 | | .51 | Coblenz, ²⁰ | .44 | Mendenhall and For- |
| Tungsten | H | 1750 | .39 | | | | .474 | Coblenz, ²⁰ | .37 | Forsythe, ²¹ 1000°, 2400° |
| | | | | | | | | Littleton, ²² 0.545 ($\lambda=0.589$) | .60 | Forsythe, ²⁴ 3000° |
| Uranium | H | <M. P. | .55 | .77 | >M. P. | .34 | | | .45 | Mendenhall and For- |
| | | | | | | | | | .66 | Forsythe, ²³ 1100°, 2900° |
| | | | | | | | | | .45 | Pirani, ²⁶ 1910, 3000° |
| | | | | | | | | | .45 | Pirani, ²⁷ 1912, 2000° |
| | | | | | | | | | .478 | Wattenberg, ²⁸ 1907, 3000° |
| | | | | | | | | | .69 | Wattenberg, ²⁹ 1910, 3000° |
| | | | | | | | | | .51 | Wattenberg, ¹³ 1910, 3000° |

¹ Drude, Wied. Annalen, **39**, p. 537, 1890.² Hagen and Rubens, Annalen der Physik, **8**, p. 16, 1902.³ Tate, Physical Review (*1*), **34**, p. 321, 1912.⁴ Tool, Physical Review (*1*), **31**, pp. 1-25, 1910.⁵ Wattenberg, Bericht der Deutschen Phys. Gesellschaft, **12**, pp. 105-127, 1910.⁶ Coblenz, Bureau of Standards Scientific Paper No. 152.⁷ Bidwell, Physical Review (*2*), **1**, pp. 482-483, 1913.⁸ Mendenhall and Forsythe, Astrophysical Journal, **37**, pp. 380-390, 1913.⁹ Forsythe, Astrophysical Journal, **34**, p. 353, 1912.¹⁰ Littleton, Physical Review, **85**, pp. 300-311, 1912.¹¹ Pirani, Verh. der Deutschen Phys. Gesellschaft, **12**, pp. 301-348, 1910.¹² Pirani, Physikalische Zeitschrift, **13**, pp. 733-754, 1912.¹³ Wattenberg, Berichte der Deutschen Chemischen Gesellschaft, **40**, p. 3287, 1907.¹⁴ Foote, Physical Review *(2)*, **34**, p. 96, 1912.

The work with oxides (see Table 2) was done with smooth surfaces, usually with material which had been melted. This gives a surface of different character from that obtained by oxidizing a relatively heavy sheet of metal in air. We should expect the values for emissivity obtained by observing these smooth surfaces to be somewhat lower than the results of other observers using the matte surface, which is usually produced when a metal is oxidized by heating in the air. Most of the published work on emissivity of oxides has been with total radiation, but the results of Burgess and Foote²⁹ on the monochromatic emissivity ($\lambda=0.65\mu$) of nickel oxide differs slightly (2 per cent) in the direction expected, while those of Pirani¹⁷ or Rubens³⁰ on thorium oxide (0.10 and 0.08, respectively) are much lower than here obtained (0.57), a difference we are unable to explain. Our observations were taken both on the oxide placed as such on the comparison strip and that obtained by melting the metal on the strip in hydrogen and oxidizing afterwards by heating in air.

TABLE 2
Measurements of Emissivity of Oxides

| Oxide of— | Atmosphere | Micropyrometer observations | | | |
|-----------|------------|-----------------------------|-------------------|-------------------|---------------------------------|
| | | Solid | | Liquid | |
| | | Temp. °C. | Emissivity | | Emissivity $\lambda=0.65\mu$ |
| | | | $\lambda=0.65\mu$ | $\lambda=0.55\mu$ | |
| Nickel | Air | 1000 | 0.89 | 1550 | 0.68 |
| | | 1200 | .83 | | |
| | | 1450 | .69 | | |
| Cobalt | Air | 1320 | .77 | 1550 | .63 |
| Iron | Air | 1200 | .63 | 1610 | .53 |
| Manganese | Air | | | 1600 | .47 |
| Titanium | Air | 1450 | .52 | 1700 | .31 |
| Thorium | Air | 1350 | .57 | | |
| Yttrium | Air | 1400 | .61 | | |
| Beryllium | Air | 1470 | .37 | | |
| Columbium | Air | 1450 | .71 | | |
| Vanadium | Air | 1160 | .69 | | |
| Chromium | Air | 1430 | .60 | | |
| Uranium | Air | 1650 | .30 | | |

²⁹ Burgess and Foote, Bureau of Standards Scientific Paper No. 224.

³⁰ Rubens, Annalen der Physik (4), 20, p. 598, 1906.

In general, the oxides have higher values of monochromatic emissivity than their metallic components, although the oxides of U, Be, Mn, and Ti appear as exceptions. More difficulty was experienced in obtaining uniform results for oxides than for metals.

For the metals, most of the observations were taken in hydrogen, thus preserving a clean surface. In those cases in which it was possible to vary the atmosphere, as for palladium, platinum, and rhodium, no difference was detected in their emissivities in air, in hydrogen, and in vacuo. Most of the white metals are seen to have emissivities, both in the red and green, lying between 0.30 and 0.45.

PHENOMENA ACCOMPANYING CHANGE OF STATE

Palladium appears to have an unstable radiation behavior after solidifying in the region of its melting point. For example, the higher value 0.38 of the emissivity for $\lambda=0.65\mu$, characteristic of the liquid surface as compared with 0.33 for the solid, will occasionally persist for some time after freezing and at temperatures well below the freezing point. We are perhaps here in the presence of a radiation phenomenon analogous to surfusion, in that the molecular mechanism of the surface to which the radiation is due may maintain its liquid characteristics after freezing.

It is also of interest to note that the emissivity of platinum for $\lambda=0.65\mu$ appears to have a well-marked discontinuity at the melting point, passing abruptly from 0.33 in the solid state to 0.38 in the liquid state, an increase in red brightness of some 15 per cent on melting. This phenomenon would tend to destroy the constancy of such a standard as the Viole unit of light, which is based on the luminous radiation from the surface of platinum at its melting point.

This discontinuity of emissivity with change of state is not limited to platinum, but is very marked with red light for gold or 0.145 to 0.219, and similarly for copper and silver, while for most of the white metals, and with green light for practically all the metals examined, this discontinuity is very slight or absent; exceptions appear to be Be, Er, Cb, and U. In the case of gold

and copper, the metals may be seen to change color, from a green to an orange, on melting. With palladium mounted on platinum the abrupt change in red brightness is easily recognized, for the palladium is practically invisible until melting takes place.

TEMPERATURE COEFFICIENT

There have been published numerous observations on the temperature coefficient of monochromatic emissivity of metals, and much of this material is inconclusive or contradictory. These results are collected in Table 1, together with observations by various observers at room temperatures, based on reflection measurements, and may be compared with the micropyrometric observations of Tables 1, 3, 5, and 6.

For both white and colored metals in the solid state it will be noted that, in general, for a given wave length the value of the emissivity of a cold metal is not very appreciably different from that of the very hot metal, the difference between observed emissivities hot and cold usually being not greater than among the values obtained by several observers at high temperatures; so that the uncertainty of the existence of a temperature coefficient of monochromatic emissivity in the visible spectrum for the temperature range 20° C to the melting point is, for metals, of the same order of uncertainty as the agreement among several observers of their observations on emissivity at any given temperature, hot or cold. For example, taking the metal for which the observations are the most numerous, the average value found by nine observers of $e_{.65\mu}$ for platinum at temperatures between 970° and 1750° is 0.316, and of three observers at 20° is 0.315. The agreement, hot and cold, is for nickel about as good, or 0.358 and 0.347, respectively. For the colored metal, gold, we apparently have $e_{.65\mu}$ equals 0.116 cold and 0.127 hot in the solid state, but the emissivity is here changing very sharply with wave length, which effect may possibly account for the difference noted. In the case of iron there appears to be a slight but well-defined negative temperature coefficient of emissivity for red light, since $e_{.65\mu}$ ranges from 0.42 at 20° C to 0.38 at 1050° and 0.36 at the melting point, 1530° C, and beyond. (See Tables 1 and 3.) Nickel oxide (Table 2) shows a negative coefficient, e for red light

decreasing from 0.89 (or 0.91 according to Burgess and Foote (*loc. cit.*) using large sheets) at 1000° C to 0.68 at the melting point, 1452° C , and beyond.

TABLE 3

Observations on Iron

[$\lambda = 0.65 \mu$ (see p. 592 for symbols)]

| Strip No. | Atmosphere | Temperature °C | | | State | Emissivity | |
|---------------|------------|----------------|------|------|--------|------------|--------|
| | | p | s | t | | Solid | Liquid |
| 103 | H | 1388 | 1400 | 1538 | Liquid | | 0.366 |
| | | 1405 | 1426 | 1559 | Liquid | | .389 |
| | | 1401 | 1412 | 1554 | Liquid | | .359 |
| | | 1297 | 1317 | 1430 | Solid | 0.399 | |
| | | 1212 | 1226 | 1330 | Solid | .382 | |
| | | 984 | 993 | 1067 | Solid | .386 | |
| 141 | H | 1383 | 1397 | 1532 | Liquid | | .372 |
| 203 | H | 1384 | 1398 | 1534 | Liquid | | .367 |
| 205 | H | 1383 | 1397 | 1532 | Liquid | | .372 |
| | | 1390 | 1405 | 1540 | Liquid | | .375 |
| 682 | H | 1374 | 1391 | 1521 | Liquid | | .382 |
| | | 1337 | 1347 | 1477 | Solid | .362 | |
| | | 1259 | 1271 | 1385 | Solid | .372 | |
| | | 1197 | 1207 | 1313 | Solid | .368 | |
| | | 1125 | 1136 | 1229 | Solid | .377 | |
| | | 973 | 982 | 1055 | Solid | .375 | |
| | | 1060 | 1070 | 1154 | Solid | .379 | |
| | | 1125 | 1137 | 1229 | Solid | .381 | |
| | | 1193 | 1206 | 1309 | Solid | .379 | |
| 683 | H | 1265 | 1277 | 1393 | Solid | .369 | |
| | | 1337 | 1348 | 1478 | Solid | .362 | |
| | | 1383 | 1393 | 1533 | Liquid | | .354 |
| | | 1331 | 1341 | 1470 | Solid | .362 | |
| | | 1257 | 1268 | 1383 | Solid | .368 | |
| | | 1187 | 1209 | 1310 | Solid | .360 | |
| | | 1059 | 1069 | 1153 | Solid | .378 | |
| | | 977 | 986 | 1060 | Solid | .374 | |
| | | 1060 | 1069 | 1154 | Solid | .375 | |
| | | 1128 | 1140 | 1233 | Solid | .376 | |
| 684 | H | 1195 | 1208 | 1311 | Solid | .380 | |
| | | 1259 | 1271 | 1386 | Solid | .370 | |
| | | 1333 | 1340 | 1473 | Solid | .350 | |
| | | 1379 | 1390 | 1528 | Solid | .360 | |
| | | 1415 | 1426 | 1571 | Liquid | | .356 |
| Mean a. d. | | 1373 | 1385 | 1521 | Liquid | | .360 |
| | | 1305 | 1319 | 1440 | Solid | .372 | |

TABLE 3—Continued
Mean of Observations on Solid Iron

| t | e |
|------|-------|
| 1530 | 0.360 |
| 1460 | .362 |
| 1390 | .370 |
| 1315 | .374 |
| 1200 | .378 |
| 1060 | .378 |

A few observations made on alloy and carbon steels indicate a slight increase in emissivity when carbon, nickel, or manganese are present in relatively considerable quantities. (See Table 4.) The average value of $e_{0.65\mu}$ for seven steels is 0.38, as compared with 0.38 to 0.36 for iron. It is hoped to make a more thorough study of the emissivity of steels.

TABLE 4
Observation on Steels
[$\lambda=0.65\mu$ (see p. 592 for symbols)]

| Strip No. | Atmosphere | Temperature ° C | | | State | Emissivity | | Analysis | | |
|-----------|------------|-----------------|------|------|--------|------------|--------|----------|-------|--------|
| | | p | s | t | | Solid | Liquid | C | Ni | Mn |
| 190 | H | 1385 | 1399 | 1535 | Liquid | | 0.368 | Per cent | 0.08 | 3.5 |
| 191 | H | 1377 | 1397 | 1525 | Liquid | | .390 | | | |
| 149 | H | 1401 | 1413 | 1554 | Liquid | | .362 | .15 | | 5.4 |
| 158 | H | 1384 | 1412 | 1534 | Liquid | | .380 | .26 | | 13.0 |
| 167 | H | 1400 | 1403 | 1552 | Liquid | | .391 | .37 | | .50 |
| 211 | H | 1355 | 1368 | 1499 | Liquid | | .367 | .23 | 15.48 | .93 |
| 398 | H | 1369 | 1383 | 1516 | Liquid | | .370 | .31 | 2.6 | Cr 1.8 |
| | | | | | | | | | Si | Mn |
| 702 | H | 1373 | 1384 | 1521 | Liquid | | .357 | .97 | .13 | .12 |
| | | 1305 | 1314 | 1440 | Solid | 0.410 | | | | |
| | | 1180 | 1197 | 1293 | Solid | .396 | | | | |
| 704 | H | 1283 | 1305 | 1414 | Solid | .400 | | | | |
| | | 1278 | 1298 | 1408 | Solid | .393 | | | | |
| | | 1151 | 1069 | 1259 | Solid | .404 | | | | |

PRECISION OF THE MEASUREMENTS

The precision obtainable in the measurement of monochromatic emissivities by the micropyrometric method is illustrated in Table 5 by the observations with red light on nickel in the range 1200°

to 1550°C , all of which observations are here recorded, giving for solid nickel $e_{0.65\mu} = 0.356 \pm 0.008$ and for the liquid 0.367 ± 0.008 with no certain evidence of temperature coefficient and slight evidence of a discontinuity at the melting point. For a substance such as gold, possessing a very low value of emissivity in the red, and for which also observations are necessarily made at lower temperatures under less sensitive conditions, the precision obtained is shown in Table 6.

TABLE 5
Observations on Nickel
[$\lambda=0.65\mu$ (see p. 592 for symbols)]

| Strip No. | Atmosphere | Temperature °C | | | State | Emissivity | |
|---------------|------------|----------------|------|------|----------------|------------|------------|
| | | p | s | t | | Solid | Liquid |
| 94 | H | 1323 | 1340 | 1461 | Liquid | | .382 |
| | | 1305 | 1309 | 1439 | Solid | 0.345 | |
| | | 1316 | 1331 | 1453 | Liquid | | .375 |
| | | 1316 | 1328 | 1453 | Liquid | | .366 |
| | | 1321 | 1335 | 1459 | Liquid | | .371 |
| | | 1238 | 1247 | 1361 | Before melting | (*.365) | |
| | | 1315 | 1324 | 1451 | Liquid | | .363 |
| | | 1268 | 1274 | 1396 | Solid | .350 | |
| | | 1383 | 1394 | 1532 | Liquid | | .362 |
| | | 1320 | 1336 | 1457 | Liquid | | .382 |
| 283 | H | 1343 | 1352 | 1485 | Liquid | | .354 |
| | | 1286 | 1288 | 1417 | Solid | .358 | |
| | | 1243 | 1249 | 1366 | Solid | .356 | |
| | | 1243 | 1246 | 1366 | Solid | .344 | |
| | | 1126 | 1134 | 1230 | Solid | .367 | |
| | | 1320 | 1330 | 1457 | Liquid | | .362 |
| | | 1330 | 1337 | 1469 | Liquid | | .350 |
| | | 1314 | 1323 | 1450 | Solid | .360 | |
| | | 1304 | 1318 | 1438 | Solid | .377 | |
| | | 1316 | 1325 | 1453 | Solid | .356 | |
| 442 | H | 1320 | 1331 | 1457 | Liquid | | .368 |
| | | 1305 | 1315 | 1440 | Solid | .358 | |
| | | 1158 | 1161 | 1268 | Solid | .340 | |
| | | 1143 | 1150 | 1250 | Solid | .358 | |
| | | 1011 | 1017 | 1098 | Solid | .361 | |
| | | 1314 | 1321 | 1450 | Solid | .354 | |
| | | 1288 | 1298 | 1419 | Solid | .368 | |
| | | 1140 | 1159 | 1258 | Solid | .336 | |
| | | | | | | .356 | .367 |
| | | | | | | $\pm .008$ | $\pm .008$ |
| Mean a. d. | | | | | | | |

* Not taken for mean.

TABLE 6
Observations on Gold

[$\lambda = 0.65 \mu$ (see p. 592 for symbols)]

| Strip No. | Atmosphere | Temperature °C | | | State | Emissivity | |
|---------------|------------|----------------|------|------|----------------|------------|--------|
| | | p | s | t | | Solid | Liquid |
| 104 | H | 1028 | 997 | 1118 | Liquid | | 0.218 |
| | | 1033 | 962 | 1134 | Solid | 0.136 | .230 |
| | | 1033 | 1006 | 1124 | Liquid | | |
| 440 | H | 922 | 860 | 997 | Before melting | (*.101) | |
| | | 935 | 886 | 1012 | Before melting | (*.154) | |
| | | 984 | 926 | 1068 | Solid | .140 | |
| | | 995 | 961 | 1080 | Liquid | | .214 |
| | | 995 | 940 | 1080 | Solid | .150 | |
| | | 993 | 938 | 1078 | Solid | .148 | |
| | | 993 | 965 | 1078 | Liquid | | .222 |
| | | 993 | 938 | 1078 | Solid | .148 | |
| | | 994 | 963 | 1079 | Liquid | | .215 |
| | | 993 | 941 | 1078 | Solid | .150 | |
| | | 989 | 926 | 1074 | Solid | .129 | |
| | | 998 | 965 | 1084 | Liquid | | .213 |
| | | 940 | 872 | 1018 | Before melting | (*.110) | |
| | | 984 | 932 | 1067 | Solid | .157 | |
| Mean a. d. | | | | | | .145 | .219 |
| | | | | | | ± .007 | ± .005 |

* Not taken for mean.

SUMMARY AND CONCLUSIONS

The micropyrometer has been shown to be an instrument comparable in accuracy and range with much more elaborate experimental installations for the determination of monochromatic emissivity. Starting with the cold substance, measurements of emissivity and of its temperature coefficient, accurate to about 1 per cent, may be taken at high temperatures (900 to 3000° C.) within a few minutes with a mass of less than 0.01 mg. presenting a surface of 0.25 mm².

Measurements of emissivity with red and green light have been made of 23 metals in hydrogen and 12 oxides in air; a summary of most of the results is given in Table 7.

TABLE 7

Emissivities of Metals and Oxides with Micropyrometer

| Metals..... | Cu | Ag | Au | Pd | Pt | Ir | Rh | Ni | Co | Fe | Mn | Ti |
|---------------------------------|------|--------------------------------|--------------------------------|--------------------------------|------------------|------------------|-------------------------------|-------|------------------|-------------------------------|--------------------------------|-------------------------------|
| $e_{\lambda=0.65}$ {solid | 0.10 | 0.04 | 0.14 | 0.33 | 0.33 | 0.30 | 0.29 | 0.36 | 0.36 | 0.37 | 0.59 | 0.63 |
| [liquid | .15 | .07 | .22 | .37 | .38 | ..... | .30 | .37 | .37 | .37 | .59 | .65 |
| $e_{\lambda=0.55}$ {solid | .38 | <.35 | <.38 | .38 | .38 | ..... | .29 | .44 | ..... | ..... | ..... | .75 |
| [liquid | .36 | <.35 | <.38 | ..... | ..... | ..... | .46 | ..... | ..... | ..... | ..... | .75 |
| Metals..... | Zr | Th | Y | Er | Be | Cb | V | Cr | Mo | W | U | |
| $e_{\lambda=0.65}$ {solid | 0.32 | 0.36 | 0.35 | 0.55 | 0.61 | 0.49 | 0.35 | 0.39 | 0.43 | 0.39 | 0.54 | ..... |
| [liquid | .30 | .40 | .35 | .38 | .61 | .40 | .32 | .39 | .40 | ..... | .34 | ..... |
| $e_{\lambda=0.55}$ {solid | .36 | ..... | ..... | ..... | .61 | .61 | .29 | .53 | ..... | ..... | .77 | ..... |
| Oxides near F. P. s..... | NiO | Co ₃ O ₄ | Fe ₃ O ₄ | Mn ₃ O ₄ | TiO ₂ | ThO ₂ | Y ₂ O ₃ | BeO | CbO _x | V ₂ O ₃ | Cr ₂ O ₃ | U ₃ O ₈ |
| $e_{\lambda=0.65}$ {solid | 0.89 | 0.77 | 0.63 | ..... | 0.52 | 0.57 | 0.61 | 0.37 | 0.71 | 0.69 | 0.60 | 0.30 |
| [liquid | .68 | .63 | .53 | 0.47 | .51 | .69 | ..... | ..... | ..... | ..... | ..... | .31 |

In the solid state practically all the metals examined appear to have a negligible or a very small temperature coefficient of emissivity for $\lambda=0.65\mu$ and $\lambda=0.55\mu$, within the temperature range 20° C. to the melting point. Nickel oxide has a well-defined negative coefficient, at least to the melting point.

There is a discontinuity in emissivity for $\lambda=0.65\mu$ at the melting point for some but not all of the metals and oxides. This effect is most marked for gold, copper, and silver, and is appreciable for platinum and palladium.

Palladium, in addition, possesses for radiation a property analogous to surfusion, in that the value of emissivity ($\lambda=0.65\mu$) natural to the liquid state may persist for a time after solidification of the metal.

The Violle unit of light does not appear to define a constant standard.

WASHINGTON, October 24, 1914.



